Theoretical and experimental considerations for neutrinoless double beta decay*

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Abstract
In the first part of this work we show some theoretical aspects of the generation of the neutrino mass by means of a direct extension of the Standard Model of particles, which include the presence of heavy right-handed neutrinos and large Majorana mass terms. From these two new ingredients, it is possible to find a mass for the light neutrinos which is naturally of the order of 1 eV or less. The idea is to put these theoretical aspects in the context of the search for neutrino mass values by the study of the signal from the Neutrinoless Double Beta Decay Process ($0\nu\beta\beta$). In the second part, a brief summary is given of the experimental considerations required for the measurement of effective Majorana neutrino mass using ($0\nu\beta\beta$). Measurement strategies and background considerations are introduced and an outline of both active and passive methods is given. Finally, current results are discussed with particular emphasis on the Heidelberg–Moscow experiment. This note is based on the presentation given at the CERN–CLAF 4th Latin American School on High-Energy Physics.

1 Theoretical aspects

1.1 Introduction

For the last few decades the Standard Model (SM) [1] has been the most accurate description for the interaction between the fundamental particles. The particles in the model are structured in three families of leptons (charged leptons and neutrinos), three families of quarks (ups and downs) and four different kinds of gauge bosons (photon, W, Z and gluons) which mediate the interactions between the fermions.

The model is constructed as a $SU(3)\times SU(2)\times U(1)$ gauge theory which is spontaneously broken by means of the Higgs mechanism [2], that allows Dirac mass terms for fermions after breaking the gauge symmetry spontaneously. The mass terms arise when the Higgs boson acquires a non-vanishing vacuum expectation value and couples to the fermions as given by the following expression:

$$\mathscr{L}_{mass} = -\lambda_f \langle H\rangle \bar{f}_L f_R + \ldots \tag{1}$$

where λ_f is the Yukawa coupling of the fermion to the Higgs, $\langle H\rangle$ is the vacuum expectation value of the Higgs, and f_L (f_R) is the left (right)-handed component of the fermion field.

Following this procedure, mass terms for the neutrinos would require a right-handed neutrino, which is not present in the minimal version of the SM. Nonetheless, observation of neutrino oscillations indicate that neutrinos have non-vanishing masses and mixings, so that their mass eigenstates differ from the flavour eigenstates [3]. Such experiments, however, can only measure the square of the differences between mass eigenstates and therefore cannot distinguish between normal and inverse mass hierarchies[1].

*Work performed as a student project under the supervision of E. Roulet.
[1] In normal (inverse) hierarchy, the neutrino with the largest (smallest) component of ν_e is the lightest.

1.2 Neutrino mass terms

Slight modifications to the SM allow one to introduce mass terms for neutrinos, either by including heavy right-handed neutrinos (with Dirac or Majorana mass terms) or a Majorana mass term for the left-handed fields. The former includes the presence of neutrinos with a chirality that has not been seen in the experiments. The Majorana mass terms couple spinors of the same chirality, but using the charge conjugation operator to allow the Lorentz invariance.

So the general expression for the mass terms of the neutrino sector is a composition of Majorana mass terms and Dirac mass terms.

$$\mathscr{L} \approx - \begin{pmatrix} \bar{\nu_L^c} & \bar{\nu_R} \end{pmatrix} \begin{pmatrix} M_L & M_D^T \\ M_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \tag{2}$$

where the dimension of this mass matrix is $(3+n) \times (3+n)$, where n is the number of the new exotic neutrinos. To allow the $SU(2) \times U(1)$ symmetry structure of the SM after including left Majorana mass terms, it is necessary to use a Higgs triplet or to set the term M_L to zero. With this last option one is left with right-handed Majorana mass terms that do not break the $SU(2) \times U(1)$ symmetry and Dirac mass terms that couple the typical left-handed neutrinos with the exotic right-handed ones.

Taking $M_R \gg M_D$, it is possible to diagonalize the above matrix by blocks (seesaw mechanism) [4] and find the effective mass matrix term for the light neutrinos

$$\mathscr{L}_{light} \approx -\bar{\nu_L^c} M_D M_R^{-1} M_D^T \nu_L \ , \tag{3}$$

now the mass matrix has dimension 3×3. From the above mass term an estimate for the mass of the light neutrinos is given by

$$\frac{m_D^2}{M_R} \approx \left(\frac{m_D}{1\,\mathrm{GeV}}\right)^2 \frac{10^{10}\,\mathrm{GeV}}{M_R} 0.1\,\mathrm{eV} \ . \tag{4}$$

1.3 Double beta decay process

The presence of a Majorana mass term implies the violation of lepton number, which is most welcome for explaining matter–antimatter asymmetry. The most promising signature of such processes is in the double beta decay, a second-order electroweak process where two neutrons from the same nucleus decay simultaneously [5].

The coupling between ν's and $\bar{\nu}$'s in Majorana terms allows for decays into a final state with no neutrinos. The Feynman diagram for the ($0\nu\beta\beta$) process is shown in Fig. 1.

The important part of the effective Hamiltonian for the ($0\nu\beta\beta$) process is given by the weak interaction term between the W gauge boson, the electron, and the neutrino mass eigenstates (N_i with masses m_i),

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[J_{\mu L}^{+} \bar{e} \gamma^{\mu} (1-\gamma_5) U_{ei} N_{Li} \right] \tag{5}$$

$$D_{\nu\nu} = i \frac{\gamma_\mu q^\mu + m_\nu}{q^2 - m_\nu^2} \tag{6}$$

where G_F is the Fermi constant, $J_{\mu L}^{+}$ is the nuclear current term, and U_{ei} are the components of the rotation matrix for the light neutrino sector. From this expression it is possible to find the amplitude for the ($0\nu\beta\beta$) process in terms of the effective neutrino mass.

$$< m_\nu >= \sum_j m_j U_{ej}^2 \ . \tag{7}$$

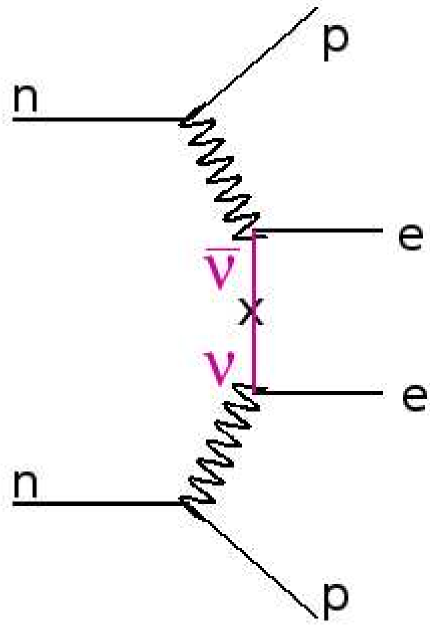

Fig. 1: Feynman diagram for the $(0\nu\beta\beta)$ process

In this way, one obtains the half-life for the neutrinoless double beta decay

$$[T_{1/2}^{0\nu\beta\beta}]^{-1} = C_1 \frac{< m_\nu >^2}{m_e^2} \; . \tag{8}$$

The measurement of such process would not only show that neutrinos have Majorana masses, but could also distinguish between the two hierarchies, as shown in Fig. 2.

2 Experimental aspects

2.1 Introduction

In the $(0\nu\beta\beta)$ decay it can be shown that the effective Majorana neutrino mass $\langle m_\nu \rangle$ can be related to the nuclear half-life $T_{1/2}^{0\nu}$ through Eq. (8). Here the C_1 factor is a combination of the phase space integral and nuclear matrix element for the decay and m_e is the electron mass. Hence to provide a measurement of $\langle m_\nu \rangle$ experimentally, or place an upper limit in the event of no signal, $T_{1/2}^{0\nu}$ is required. As a higher order process the half-life is expected to be in excess of 10^{20} yrs. It follows that $T_{1/2}^{0\nu}$ can be obtained to first order from the nuclear decay law

$$T_{1/2}^{0\nu} = \ln 2 \frac{a N_A m t}{N_{0\nu}}, \; (T_{1/2}^{0\nu} \gg t). \tag{9}$$

Here a is the natural abundance of the isotope considered, m the total mass used, and N_A the Avogadro number. $N_{0\nu}$ is the number of $(0\nu\beta\beta)$ decays observed during the experiment lifetime t.

2.2 Experimental strategy

The experimental signature of $(0\nu\beta\beta)$ consists of two electrons in the final state with no missing energy [6]. This is in contrast to the standard double beta decay which shows a continuous spectrum due to energy carried away by neutrinos. Figure 3 shows schematically the energy spectrum for these respective modes. It can be seen that the $(0\nu\beta\beta)$ mode peaks at the transitional Q-value and is in stark contrast with

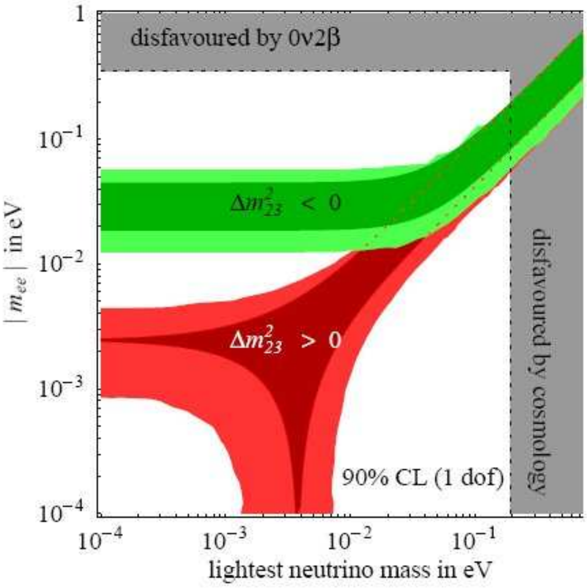

Fig. 2: Boundary limits to the mass of the lightest neutrino vs. the effective ($0\nu\beta\beta$) mass from neutrino oscillation experiments. The green curve is for normal hierarchy and the red curve is for inverse hierarchy.

the standard mode; however, as the tail of the standard mode approaches the Q-value it will contribute to ($0\nu\beta\beta$) background. Differences in scaling of each of these modes with Q means that to reduce this background it is more desirable to use isotopes with Q-value $> 2\,\text{MeV}$ for experiment. There are eleven candidate isotopes which meet this requirement, a list of which is given in Ref. [7]. Experiments also require large m if a signal is to be detected. For example ^{100}Mo with assumed $T^{0\nu}_{1/2} \sim 10^{26}$ yrs would require $m > 100\,\text{kg}$ for one signal decay per year [7].

2.3 Background

The large half-life for ($0\nu\beta\beta$) decay makes observation over backgrounds particularly challenging since there are relatively few signal events. Furthermore in the background-limited case the experimental dependence of the half-life goes as

$$T^{0\nu}_{1/2} \propto a\epsilon\sqrt{\frac{mt}{\Delta E \cdot B}}\,. \tag{10}$$

Here ϵ is the detection efficiency, ΔE the energy resolution at the Q-value peak, and B the background index in evts/yr/keV/kg [7]. In contrast to the background-free case in (2) here the half-life increases with the square root of m and t, hence background limits the effect of increasing these variables. Background can originate from a variety of sources including natural uranium and thorium decays, atmospheric muons, and radioisotopes.

2.4 Detector types

Two main detector types exist in ($0\nu\beta\beta$) experiments. In active detectors the source and detector are the same, for example Ge-semiconductor devices. This has the advantage that the detection efficiency will be high, however, it is common in the active case that only the sum energy of the electrons can be measured. Passive detectors surround the source with detectors for both tracking and calorimetry which can increase the experimental resolution on individual electrons, however, in this case the source strength will be lower.

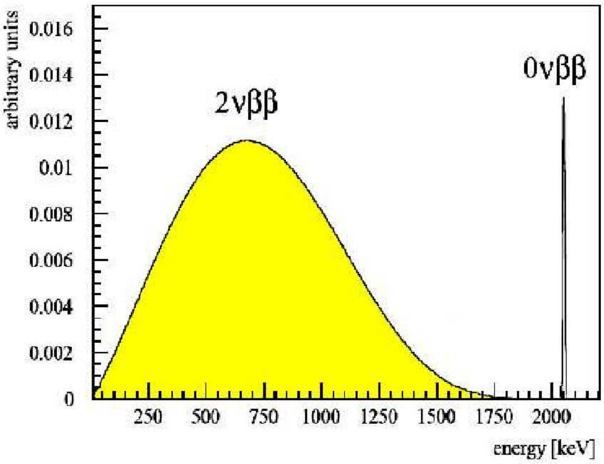

Fig. 3: Energy spectrum for standard double beta decay $(2\nu\beta\beta)$ compared to $(0\nu\beta\beta)$ for the ^{76}Ge Q-value. Note that the scale of the ordinate axis is arbitrary and the $(0\nu\beta\beta)$ signal is greatly exaggerated.

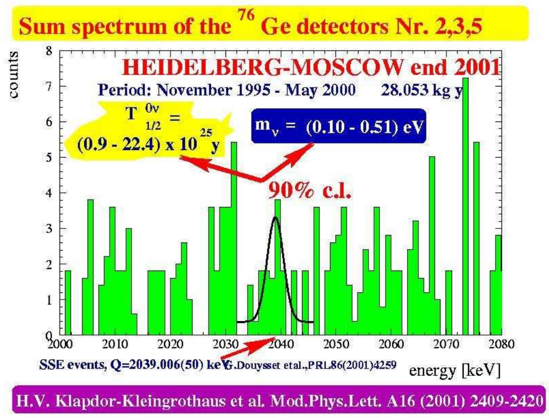

Fig. 4: The claim by the Heidelberg–Moscow experiment to have seen $(0\nu\beta\beta)$ at the 2σ level is shown in this plot. This observation remains controversial.

2.5 The Heidelberg–Moscow experiment

The Heidelberg–Moscow experiment at the Gran Sasso Laboratory ran from 1990 to 2003 and was an example of an active Ge-semiconductor device. The isotope of interest is ^{76}Ge with a Q-value of 2039 keV. Initially the collaboration reported no signal and placed a lower limit of $T^{0\nu}_{1/2} > 1.92 \times 10^{25}$ yrs at the 90% CL, corresponding to an upper limit of $\langle m_\nu \rangle < 0.35$ eV [8]. However, following this, some members of the collaboration reported seeing signal at the 2σ level, shown in Fig. 4 [9]. This analysis has since been updated and now claims a 4.2σ measurement with $T^{0\nu}_{1/2} = 0.69 - 4.18 \times 10^{25}$ yrs corresponding to $\langle m_\nu \rangle = 0.24$–$0.58$ eV [10]. If correct this result would imply a degenerate neutrino mass hierarchy, however, this result has been criticised in the literature and remains controversial [7]. It is hoped that the proposed GERDA experiment [11], also at Gran Sasso, which uses the same detection concept will settle this controversy.

3 Conclusion

In the theoretical part we described the minimal extension of the SM that makes possible a mass term for the light neutrinos. Using this formalism we can compute the half-life time for the $(0\nu\beta\beta)$ process, and see that this is proportional to the effective neutrino mass, which involves the Majorana nature of the neutrinos. From experimental bounds we can constrain the allowed parameter space for this quantity in two different scenarios that define the mass hierarchy of the neutrino sector.

In the experimental part we see that the signal of the $(0\nu\beta\beta)$ decay is a very rare process, and the experiments until now just give us upper limits in the neutrino mass and some controversial results involving possible positive signals of $(0\nu\beta\beta)$ decays. In addition, we see that the background is a significant experimental challenge, whose treatment should improve with advances in experimental techniques. Hence we hope that the next generation of these experiments together with the contribution from neutrino oscillations experiments will give us more accurate information about these mysterious particles.

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